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(54) Abstract Title: **Cancellation of borehole effects for well logging**

(57) Methods and apparatus for making subsurface measurements with reduced or eliminated borehole effects employ electrodes to cancel undesired axially induced currents when tilted or transverse antennas are used. A sonde comprising at least one tilted or TMD antenna (Tx, Rx) has a pair of electrodes (E1, E2) linked to one another wherein they may be open or short circuited in order to cancel axial currents induced in the borehole when the sonde is perpendicularly eccentered therein. The electrodes may be operated passively, actively or semi-actively to limit the current flow.

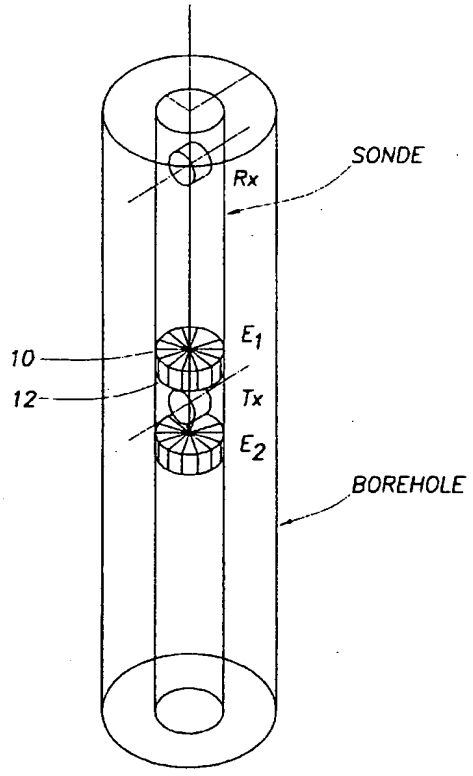

FIG.2

GB 2 393 255 A

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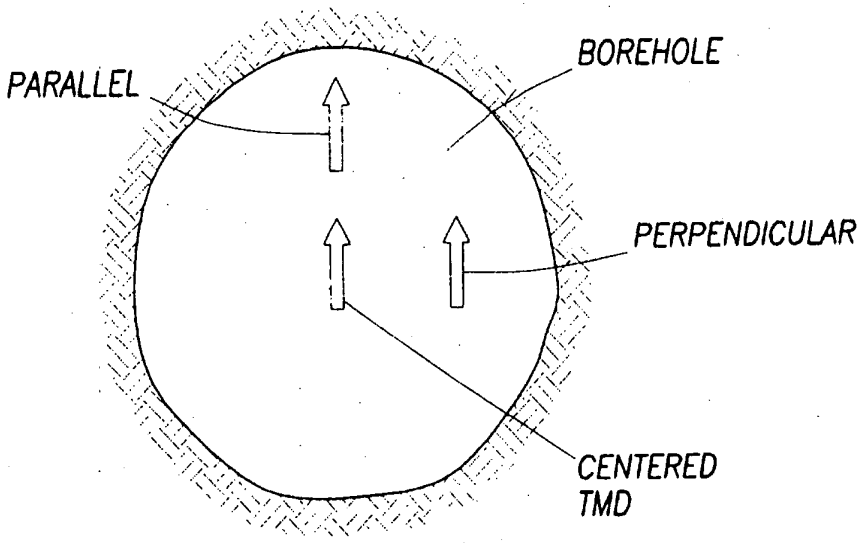
PARALLEL
BOREHOLE
PERPENDICULAR
CENTERED
TMD

FIG. 1

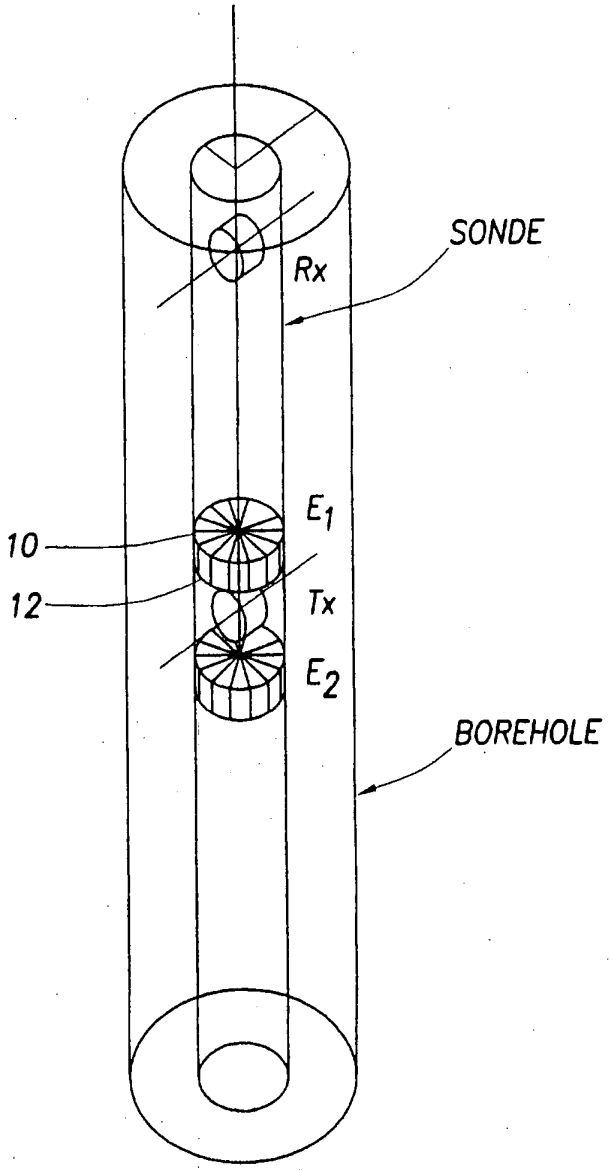
SONDE
Rx
E_1
10
12
Tx
E_2
BOREHOLE

FIG. 2

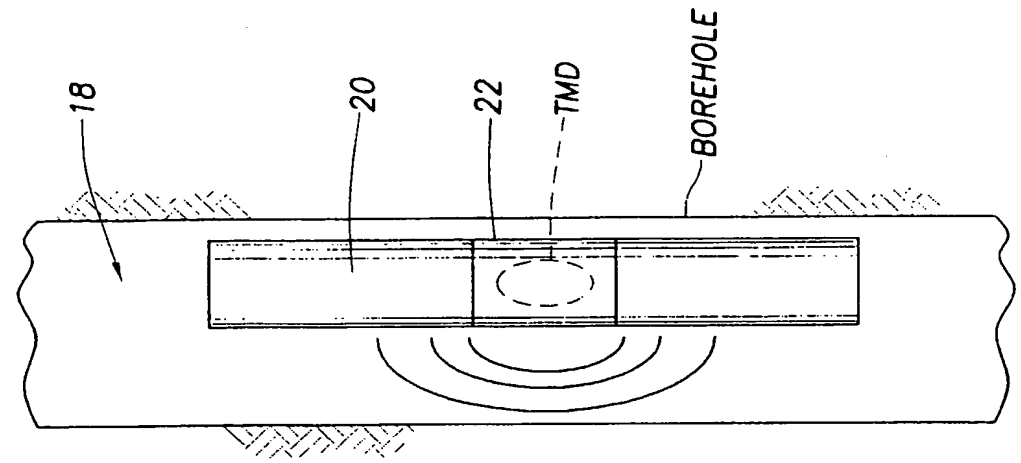

FIG.5

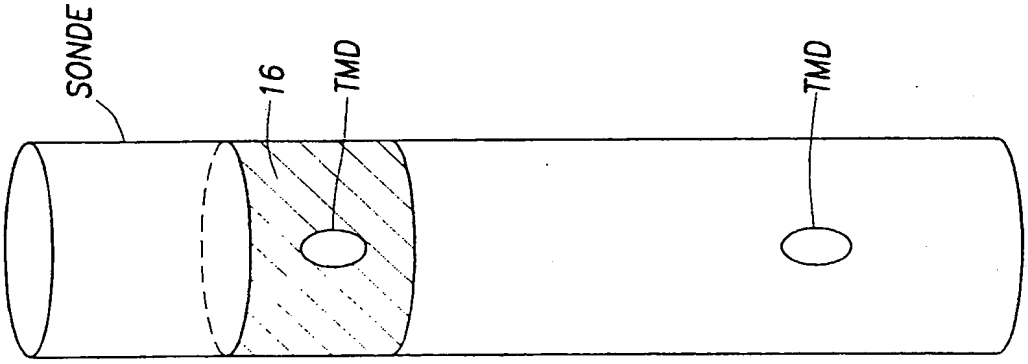

FIG.4

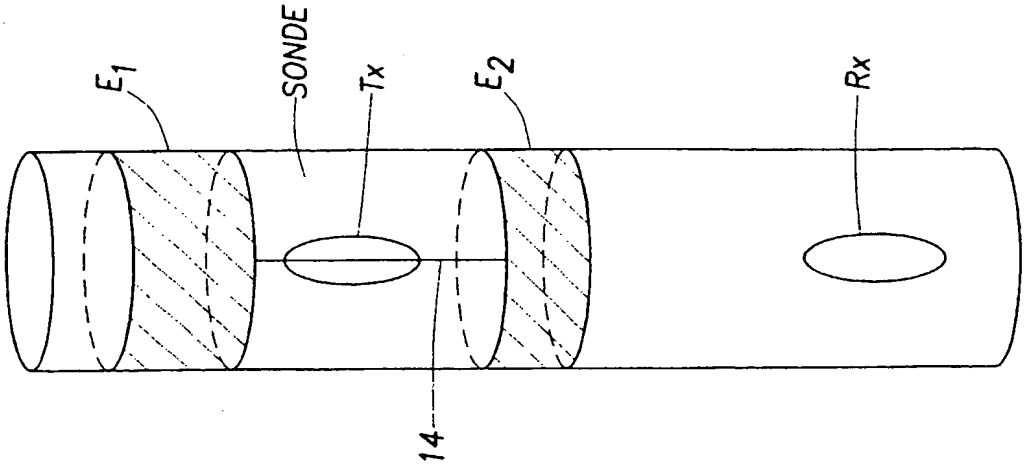

FIG.3

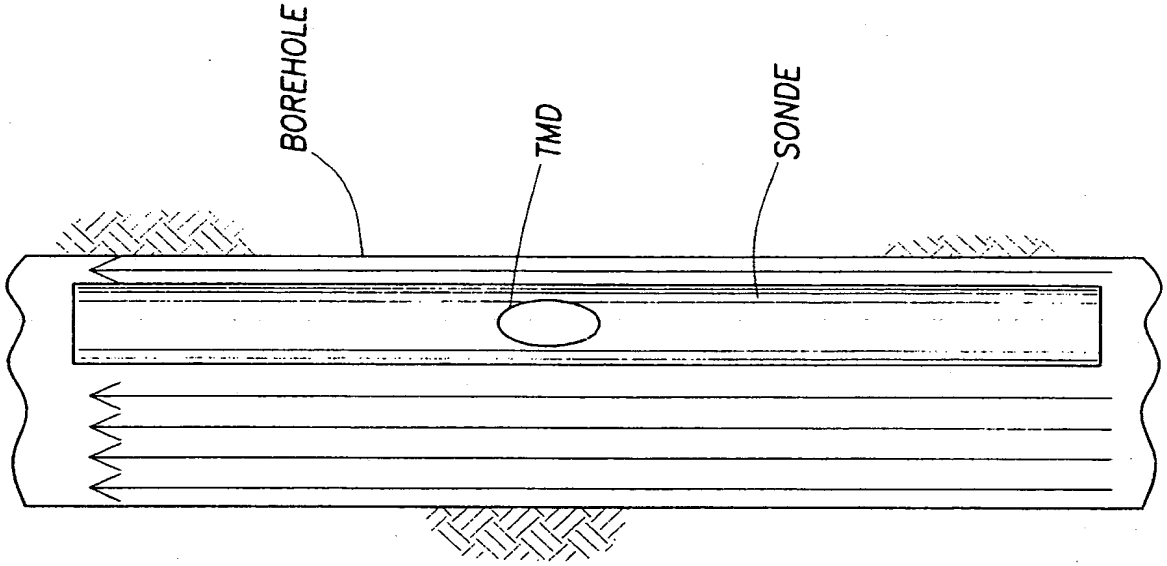

FIG.8

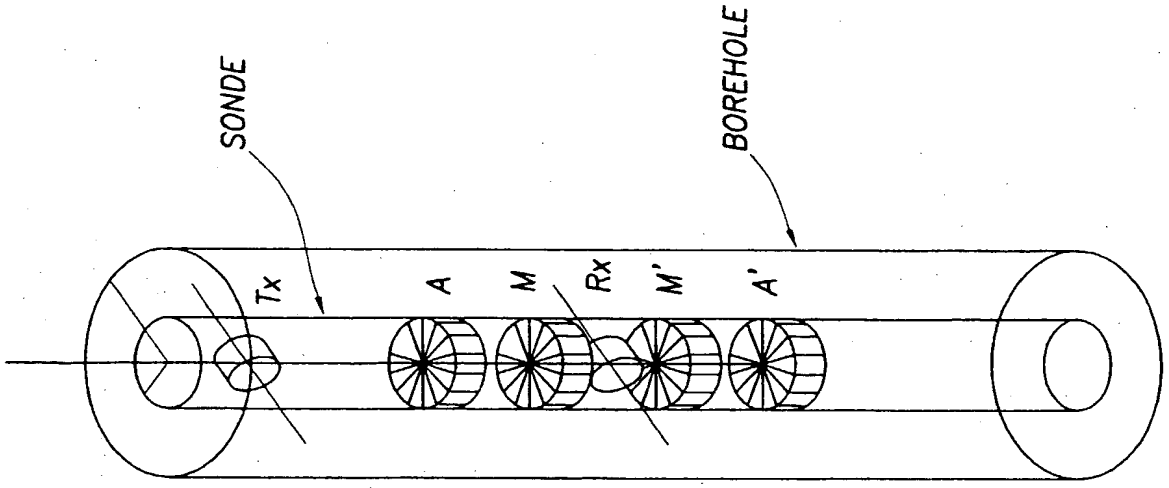

FIG.6

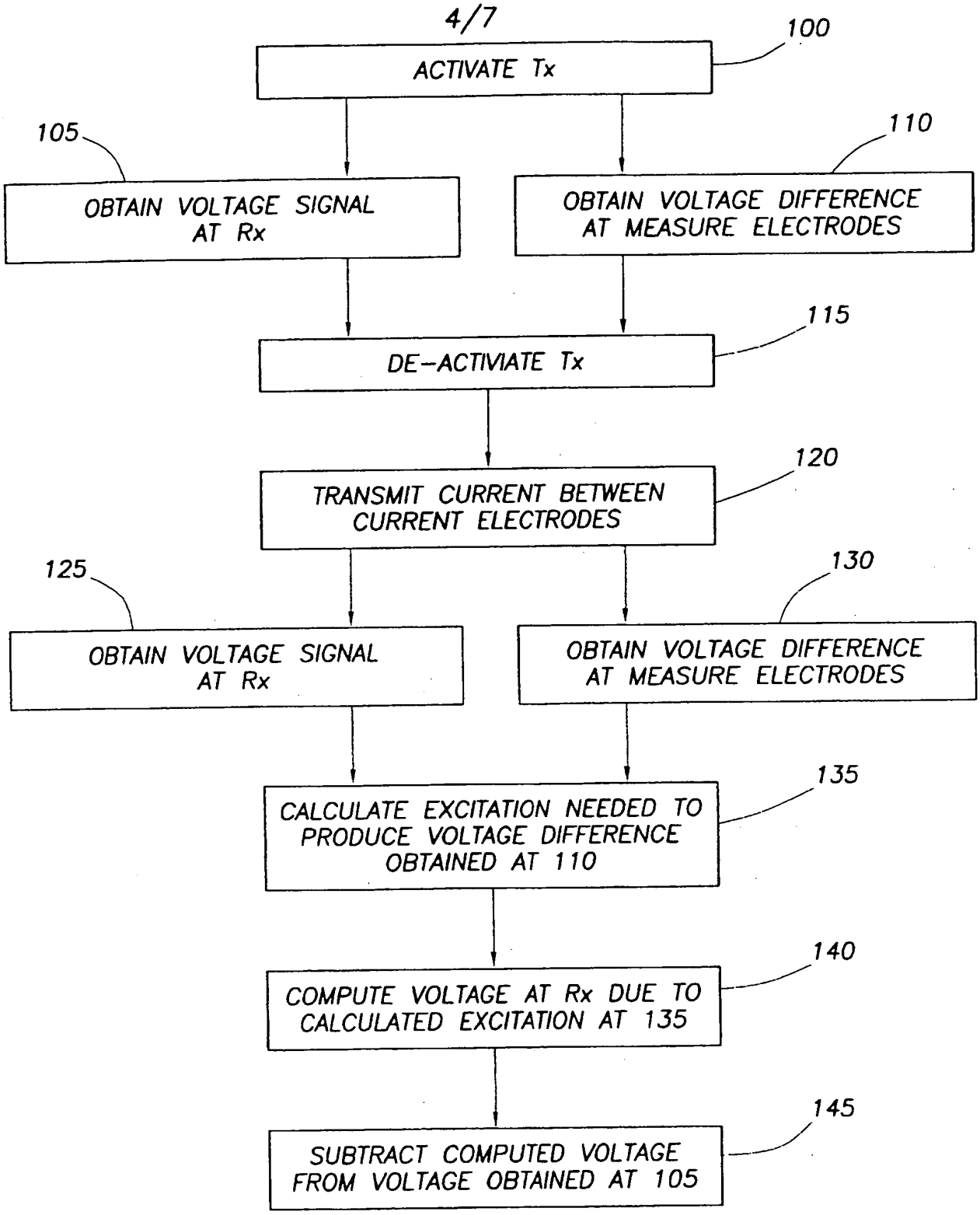
ACTIVATE Tx
100
105
OBTAIN VOLTAGE SIGNAL AT Rx
110
OBTAIN VOLTAGE DIFFERENCE AT MEASURE ELECTRODES
115
DE-ACTIVIATE Tx
120
TRANSMIT CURRENT BETWEEN CURRENT ELECTRODES
125
OBTAIN VOLTAGE SIGNAL AT Rx
130
OBTAIN VOLTAGE DIFFERENCE AT MEASURE ELECTRODES
135
CALCULATE EXCITATION NEEDED TO PRODUCE VOLTAGE DIFFERENCE OBTAINED AT 110
140
COMPUTE VOLTAGE AT Rx DUE TO CALCULATED EXCITATION AT 135
145
SUBTRACT COMPUTED VOLTAGE FROM VOLTAGE OBTAINED AT 105

FIG.7

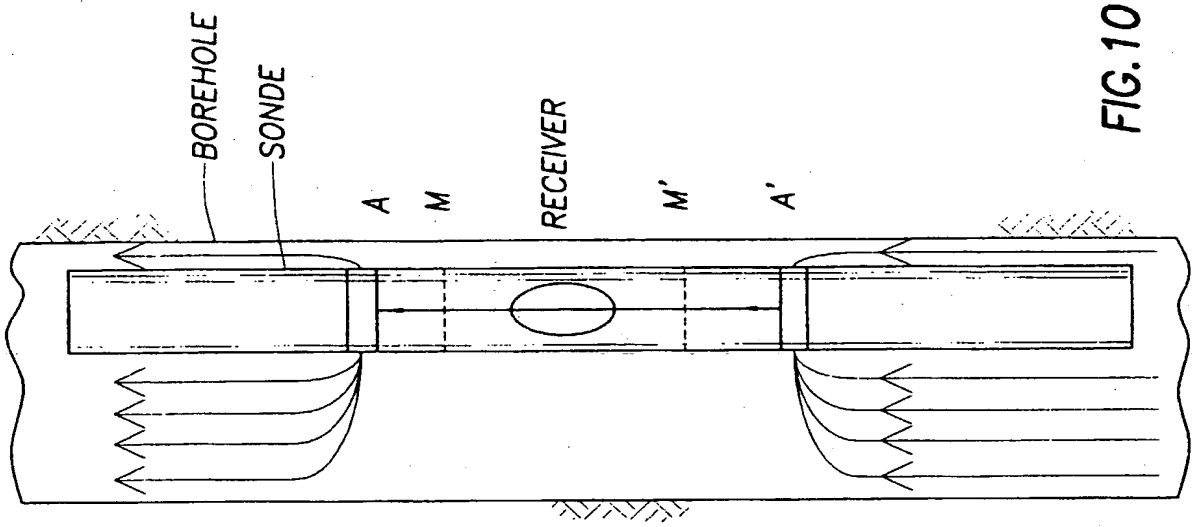
BOREHOLE
SONDE
A
M
RECEIVER
M'
A'

FIG.10

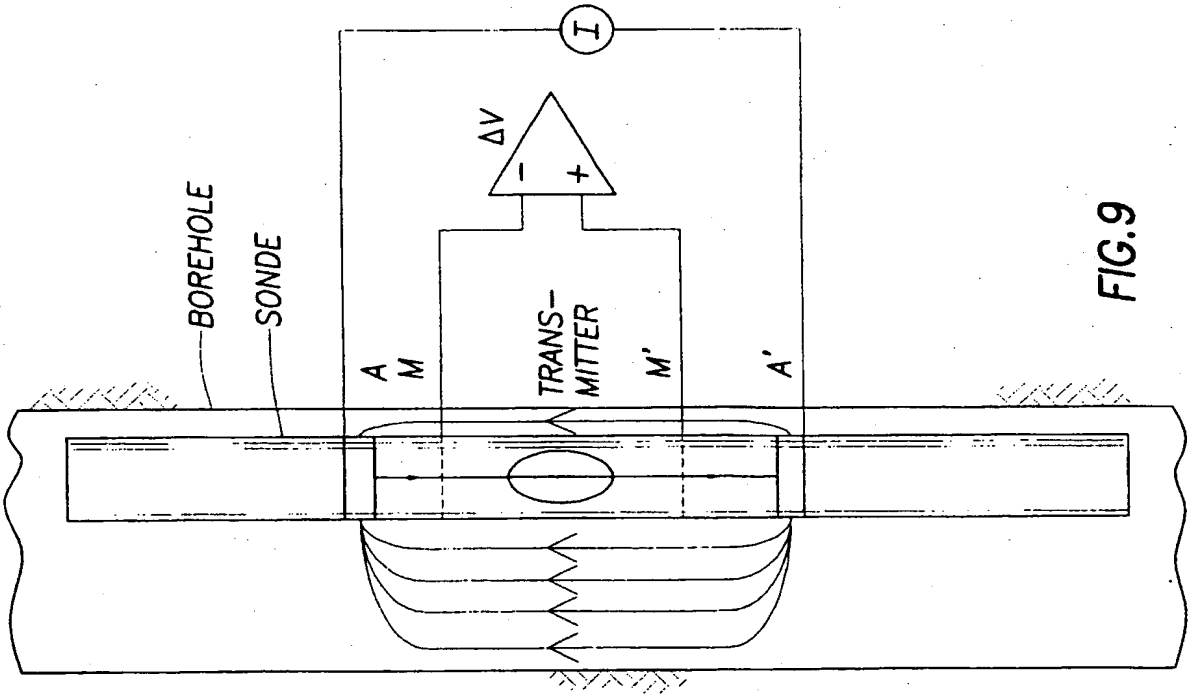
I
ΔV
-
+
BOREHOLE
SONDE
A
M
TRANS-
MITTER
M'
A'

FIG.9

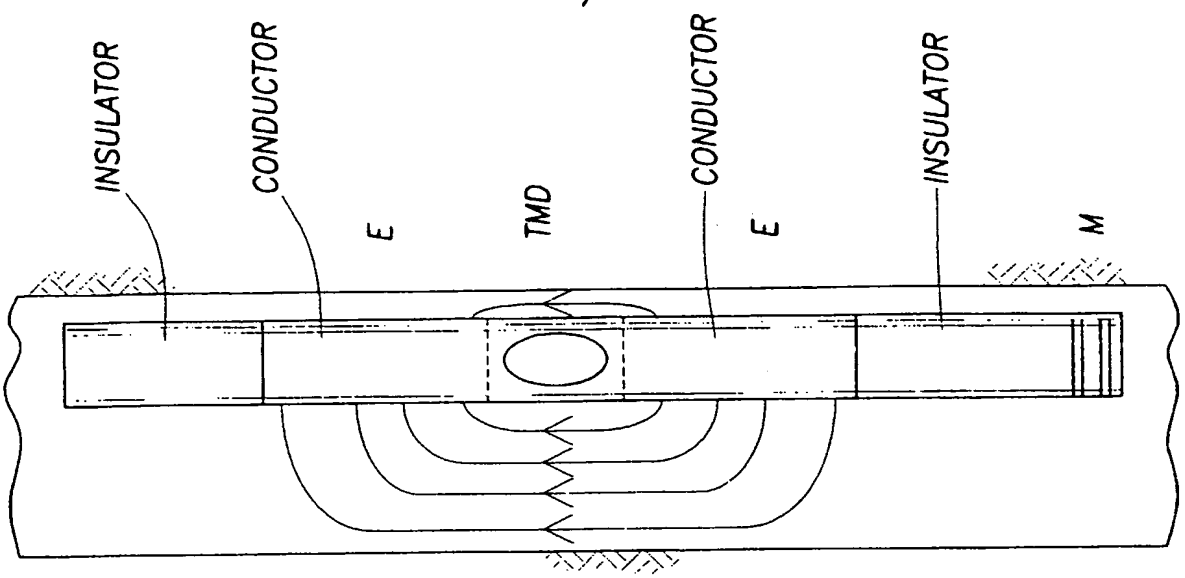

FIG.11b

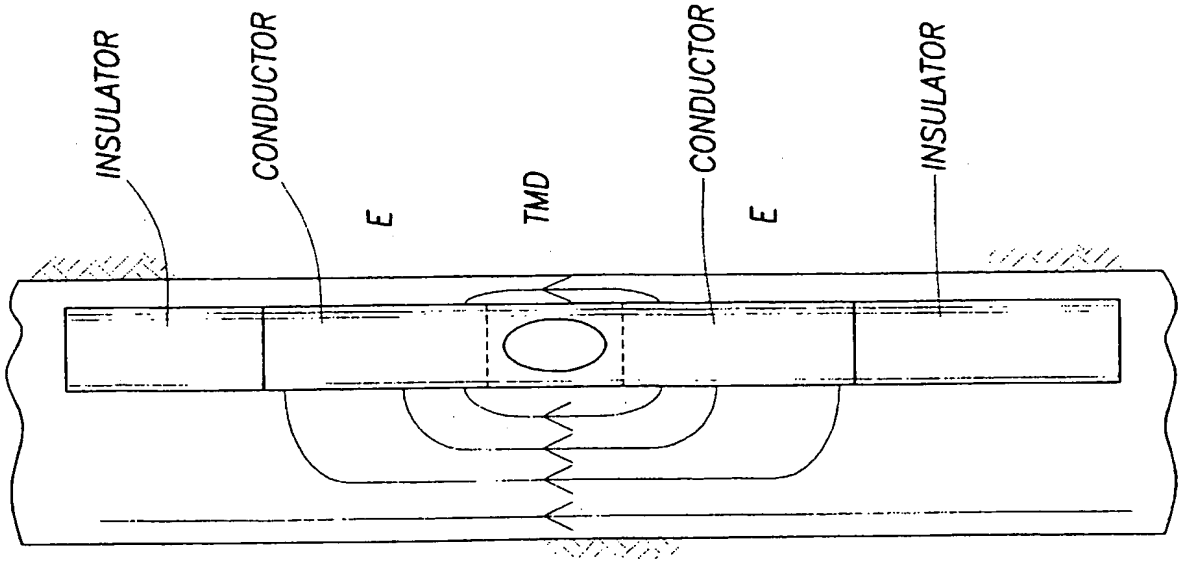

FIG.11a

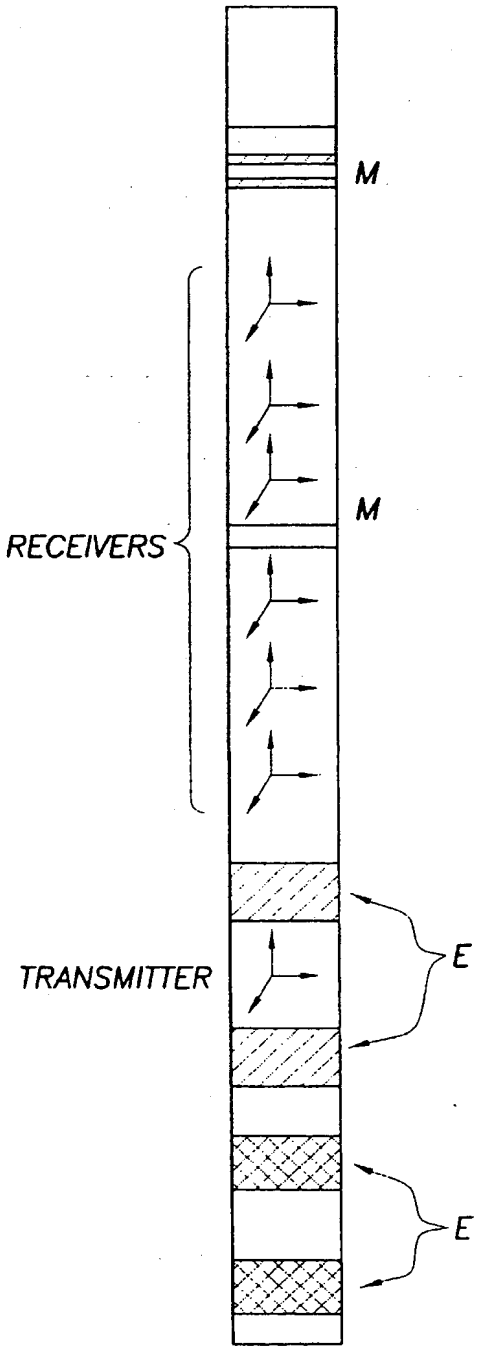

FIG. 12

PASSIVE, ACTIVE, AND SEMI-ACTIVE CANCELLATION OF BOREHOLE EFFECTS FOR WELL LOGGING

1. BACKGROUND OF THE INVENTION

1.1 Field of the Invention

The invention relates to techniques for reducing and/or correcting for borehole effects encountered in subsurface measurements. More particularly, the invention concerns methods, and devices for their implementation, to reduce or correct for undesired electromagnetic effects associated with the deployment of antennas having transverse or tilted axes within a borehole.

1.2 Description of Related Art

Various well logging techniques are known in the field of hydrocarbon exploration and production. These techniques typically employ logging instruments or "sondes" equipped with sources adapted to emit energy through a borehole traversing the subsurface formation. The emitted energy interacts with the surrounding formation to produce signals that are detected and measured by one or more sensors on the instrument. By processing the detected signal data, a profile of the formation properties is obtained.

Electromagnetic (EM) logging techniques known in the art include "wireline" logging and logging-while-drilling (LWD). Wireline logging entails lowering the instrument into the borehole at the end of an electrical cable to obtain the subsurface measurements as the instrument is moved along the borehole. LWD entails attaching the instrument disposed in a drill collar to a drilling assembly while a borehole is being drilled through earth formations.

Conventional wireline and LWD instruments are implemented with antennas that are operable as sources and/or sensors. In wireline applications, the antennas are typically enclosed by a housing constructed of a tough plastic material composed of a laminated fiberglass material impregnated with epoxy resin. In LWD applications, the antennas are generally mounted on a metallic support to withstand the hostile environment encountered during drilling. Conventional logging instruments are also being constructed of thermoplastic materials. The thermoplastic composite construction of these instruments provides a non-conductive structure for mounting the antennas. U.S. Pat. No. 6,084,052 (assigned to the present assignee) describes implementations of composite-based logging instruments for use in wireline and LWD applications.

In both wireline and LWD applications, the antennas are mounted on the support member and axially spaced from each other in the direction of the borehole. These antennas are generally coils of the cylindrical solenoid type and are comprised of one or more turns of insulated conductor wire that is wound around the support. U.S. Pat. Nos. 4,873,488 and 5,235,285 (both assigned to the present assignee), for example, describe instruments equipped with antennas disposed along a central metallic support. In operation, the transmitter antenna is energized by an alternating current to emit EM energy through the borehole fluid (also referred to herein as mud) and into the formation. The signals detected at the receiver antenna are usually expressed as a complex number (phasor voltage) and reflect interaction with the mud and the formation.

One EM logging technique investigates subsurface formations by obtaining electrical resistivity or conductivity logs by "focused" measurements. U.S. Pat. No. 3,452,269 (assigned to the present assignee) describes an instrument adapted for taking these focused measurements. The technique described in the '269 patent uses a survey current emitted by a principal survey current emitting electrode. This survey current is confined to a path substantially perpendicular to the borehole axis by focusing currents emitted from nearby focusing electrodes. U.S. Pat. No. 3,305,771 describes a focusing technique using an instrument equipped with toroidal coils. U.S. Pat. Nos. 3,772,589, 4,087,740, 4,286,217 (all assigned to the present assignee) describe other electrode-type instruments used for subsurface measurements.

U.S. Pat. No. 5,426,368 (assigned to the present assignee) describes a logging technique using an array of current electrodes disposed on a support. The '368 patent uses the electrode configuration to investigate the geometrical characteristics of the borehole and the resistivity properties of the formation. U.S. Pat. Nos. 5,235,285 and 5,339,037 (both assigned to the present assignee) describe metallic instruments adapted with a toroidal coil and electrode system for obtaining resistivity measurements while drilling. The measurement techniques described in the '285 and '037 patents entail inducing a current that travels in a path including the conductive support body and the formation.

U.S. Pat. Nos. 3,388,325 and 3,329,889 (both assigned to the present assignee) describe instruments equipped with an electrode and coil configuration for obtaining subsurface measurements. U.S. Pat. No. 3,760,260 (assigned to the present assignee) also describes a downhole instrument equipped with electrodes and coils. The '260 patent uses the electrode configuration to ensure radial current flow into the formation surrounding the

borehole. U.S. Pat. No. 4,511,843 (assigned to the present assignee) describes a logging technique whereby currents are emitted from electrodes to zero a potential difference between other electrodes on the instrument. U.S. Pat. No. 4,538,109 (assigned to the present assignee) describes a logging technique aimed at correcting or canceling the effects of spurious EM components on downhole measurement signals.

A coil carrying a current can be represented as a magnetic dipole having a magnetic moment proportional to the current and the area. The direction and strength of the magnetic moment can be represented by a vector perpendicular to the plane of the coil. In conventional induction and propagation logging instruments, the transmitter and receiver antennas are mounted with their axes along the longitudinal axis of the instrument. Thus, these instruments are implemented with antennas having longitudinal magnetic dipoles (LMD). When such an antenna is placed in a borehole and energized to transmit EM energy, currents flow around the antenna in the borehole and in the surrounding formation. There is no net current flow up or down the borehole.

An emerging technique in the field of well logging is the use of instruments incorporating antennas having tilted or transverse coils, i.e., where the coil's axis is not parallel to the support axis. These instruments are thus implemented with antennas having a transverse or tilted magnetic dipole (TMD). The aim of these TMD configurations is to provide EM measurements with directed sensitivity and sensitivity to the anisotropic resistivity properties of the formation. Logging instruments equipped with TMDs are described in U.S. Pat. Nos. 4,319,191, 5,508,616, 5,757,191, 5,781,436, 6,044,325, 6,147,496, WO 00/50926, and in V. F. Mechetin et al., *TEMP- A New Dual Electromagnetic and Laterolog Apparatus-Technological Complex*, THIRTEENTH EUROPEAN FORMATION EVALUATION SYMPOSIUM TRANSACTIONS, Budapest Chapter, paper K, 1990.

A particularly troublesome property of the TMD is the extremely large borehole effect that occurs in high contrast situations, i.e., when the mud in the borehole is much more conductive than the formation. When a TMD is placed in the center of a borehole, there is no net current along the borehole axis. When it is eccentered in a direction parallel to the direction of the magnetic moment, the symmetry of the situation insures that there is still no net current along the borehole axis. However, when a TMD is eccentered in a direction perpendicular to the direction of the magnetic moment, axial currents are induced in the borehole. In high contrast situations these currents can flow for a very long distance along the

borehole. When these currents pass by TMD receivers, they can cause undesired signals that are many times larger than would appear in a homogeneous formation without a borehole.

U.S. Pat. No. 5,041,975 (assigned to the present assignee) describes a technique for processing signal data from downhole measurements in an effort to correct for borehole effects. U.S. Pat. No. 5,058,077 describes a technique for processing downhole sensor data in an effort to compensate for the effect of eccentric rotation on the sensor while drilling. However, neither of these patents relates to the properties or effects of TMDs in subsurface measurements.

Thus there remains a need for improved methods and apparatus for reducing or correcting for these currents when using well logging instruments implemented with TMDs.

2. SUMMARY OF THE INVENTION

The invention provides an apparatus for use in a borehole traversing a subsurface formation, comprising an elongated support having a longitudinal axis; at least one antenna disposed on the support such that its axis is tilted or perpendicular with respect to the support axis, each antenna adapted to transmit or receive electromagnetic energy; and a pair of electrodes disposed on the support, the electrodes linked to one another for joint electromagnetic interaction; wherein the electrodes of the electrode pair are adapted to selectively form a short or open circuit between the electrodes.

The invention also provides a method for making a subsurface measurement. The method comprises transmitting electromagnetic energy from an antenna disposed within a subsurface borehole with its axis tilted or perpendicular with respect to the borehole axis; detecting a current flow along the borehole, the current flow associated with the electromagnetic energy transmission, with a first pair of electrodes disposed within the borehole; and emitting a current between a second pair of electrodes disposed within the borehole in response to the current flow detected at the first electrode pair to reduce the current flow; and determining a voltage signal associated with the transmitted energy.

3. BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

Figure 1 shows a pictorial looking downhole of parallel and perpendicular eccentering of a tilted or transverse magnetic dipole within a borehole.

Figure 2 is a schematic diagram of an instrument with an arrayed electrode configuration according to the invention.

Figure 3 is a schematic diagram of an instrument with an annular electrode configuration according to the invention.

Figure 4 is a schematic diagram of an instrument with a conductive segment disposed on a non-conductive support according to the invention.

Figure 5 is a schematic diagram illustrating the current paths encountered with a conductive all-metal instrument having a perpendicularly eccentered tilted or transverse magnetic dipole in accord with the invention.

Figure 6 is a schematic diagram of an instrument with multiple electrode pairs configured about an antenna according to the invention.

Figure 7 shows a flow chart of an embodiment of a method according to the invention.

Figure 8 is a schematic diagram of the induced axial current flow encountered in the borehole with a non-conductive instrument having a perpendicularly eccentered tilted or transverse magnetic dipole.

Figure 9 illustrates the current injected into the borehole from an instrument equipped with electrode pairs about a source according to the invention.

Figure 10 is a schematic diagram of the axial current flow about an instrument equipped with electrode pairs about a sensor according to the invention.

Figure 11a is a schematic diagram of the axial current flow about an instrument equipped with an antenna having a tilted or transverse axis.

Figure 11b is a schematic diagram of the axial current flow about an instrument equipped with electrode pairs about antenna according to the invention.

Figure 12 is a schematic diagram of an instrument with multiple current and measure electrode pairs disposed about an antenna configuration according to the invention.

4. DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Before proceeding with disclosure of the invention, some theoretical consideration shall be set forth.

A TMD can be eccentered in a borehole in two possible orientations, which we will call parallel and perpendicular eccentering as shown in Figure 1. Parallel eccentering forces currents symmetrically up and down the borehole and therefore no net current is generated. This borehole effect is no worse than in a typical downhole instrument equipped with non-

tilted (axial) antennas. Perpendicular eccentering gives rise to a large axial borehole current in the case of an insulated instrument body, which strongly couples to a transverse receiver an axial distance away (not shown). These two displacements are the extremes of the possible ones. In the general case, the eccentering will be in a direction that is at some angle to the dipole moment of the sensors. In this case, the borehole effect lies between the two extreme cases.

It is important to understand the basic difference between the borehole effect of a conventional LMD and the borehole effect of a TMD. If either type of source is placed in a homogeneous medium, currents will flow in paths surrounding the transmitter. When a borehole is added, these current paths are distorted. These currents induce a voltage in a receiver coil displaced from the transmitter. This voltage is an indication of the resistivity of the formation. If instead of a homogeneous medium, we include a borehole, then the current paths are altered and hence the received voltage is different from what would be measured in the absence of a borehole. This difference is called the "borehole effect." The difference in borehole effect between an LMD and a TMD is due to the difference between the distortion of the currents in the presence of a borehole. With an LMD centered or eccentered in a borehole, these currents flow in the borehole in a region near the transmitter. We know that the field of a localized current distribution can be represented as by a multipole expansion. The leading term (the dipole term) falls off as $1/r^3$, where r is the radial distance in any direction away from the transmitter. Other terms fall off even faster.

For a TMD eccentered in a borehole in a direction along the direction of the dipole moment (parallel), we have a similar situation. Currents flow up one side of the borehole and down the other in a symmetric manner. There is no net current in the borehole past the transmitter. This localized current causes a dipole field just as with an LMD. When the TMD is eccentered in a direction perpendicular to the direction of the dipole moment, these currents are no longer symmetric and a net current flows in the borehole past the transmitter. This current flows up the borehole and returns through the formation. When this current passes the receiver coil, a voltage is induced in the coil. This current falls off, not geometrically at least as rapidly as $1/r^3$, but exponentially as $e^{-(z/z_0)}$ where z_0 is proportional to $\sqrt{\frac{R_{formation}}{R_{mud}}}$. When the borehole is much more conductive than the formation, this leads to a very slow falloff in this current.

In the case of an LMD, or a parallel eccentered TMD, the voltage in the receiver is due to the fields from the localized distortion of the current distribution near the transmitter. In the case of a perpendicularly eccentered TMD, it is due to the field from a current travelling in the borehole right past the receiver. This second effect is much larger than the first.

Figure 2 shows an embodiment of the invention. A logging instrument with a non-conductive body is shown disposed within a borehole. The instrument is equipped with a transverse (90° axis tilt) transmitter antenna Tx and a transverse receiver antenna Rx. The instrument is also equipped with a pair of electrodes E_1, E_2 positioned at opposite ends of the transmitter antenna Tx. The electrodes E_1, E_2 may be formed as an array of circumferentially spaced apart azimuthal metallic electrodes. Figure 2 shows an electrode configuration composed of an array of sixteen discrete azimuthal metallic segments 10 mounted on an insulating toroid 12. Alternatively, the electrodes E_1, E_2 may also be formed as one-piece metallic annular electrodes as shown in Figure 3. If an annular electrode configuration is used, it is preferable to leave an axial gap or opening along the circumference of the electrode. It will be appreciated by those skilled in the art that various types of electrode configurations may be used to implement the invention as known in the art, such as button electrodes.

The electrodes E_1, E_2 are shorted together with a conductor (e.g., a wire, cable, or metallic strap) 14 that preferably runs through the center of the transmitter antenna Tx. If the electrodes E_1, E_2 are configured as an array of circumferentially spaced apart azimuthal electrodes, all the electrode segments of E_1 are shorted together and all the electrode segments of E_2 are shorted together and E_1 is shorted to E_2. The shorting of the electrodes E_1 and the shorting of the electrodes E_2 is preferably done with wires that run radially to avoid the formation of an azimuthal current loop. By shorting the electrodes E_1, E_2 above and below the transmitter Tx, this configuration insures that there is no net electric field along the borehole and so no net current flow. The conductor(s) connecting upper and lower electrodes E_1, E_2 pass through the transmitter Tx and allow currents flowing through the borehole to close. This leads to a localized current distribution without the long-range axial currents, which would otherwise be present in the borehole. This localized distribution of currents has, at most, a dipole moment which falls off at least as fast as $1/L^3$, where L is the spacing between antennas. In effect, this configuration shorts the azimuthally varying induced axial current through the transmitter Tx and forms a local magnetic dipole in opposition to the

TMD. The electrodes E_1, E_2 may be mounted on the instrument by any suitable means known in the art.

Figure 4 shows another embodiment of the invention. By mounting the TMD about a conductive segment 16 disposed along the non-conductive support member of the instrument, a local induced current distribution is formed. The current loop that is created is composed of the borehole and conductive segment 16. The conductive segment 16 may be formed as a metallic tube or sleeve mounted on the non-conductive support. The instrument may be equipped with multiple conductive segments and antennas as desired. Modeling and experiments show that the current that flows in the borehole and metal section of the instrument is limited in axial extent to a few times the borehole diameter. Thus the length of the conductive section is variable, but preferably more than a few times the diameter of the largest borehole where the instrument may be run.

With the conductive segment 16 disposed in alignment with an antenna and in contact with the borehole fluid, the axial current induced in the borehole returns through the instrument body in the vicinity of the antenna instead of traveling for a long distance along the borehole. If the conductive segment 16 is about the receiver antenna, then the axial current that would otherwise travel in the borehole will instead travel in the conductive segment 16. Thus, the flow of the induced axial current along the borehole is minimized by providing an alternate path for the current along the instrument body. An alternative embodiment extends the conductive segment 16 to the length of the instrument (not shown), in essence consisting of a full-metal sleeve along the support.

Conventional induction logging instruments, particularly wireline instruments, comprise antennas in housings formed of non-conductive materials such as fiberglass reinforced epoxy resin. Figure 5 shows another embodiment of the invention. A TMD antenna is disposed on a logging instrument 18 consisting of an all-metal body 20. A layer of an electrically insulating material (e.g., Randallite, fiberglass-epoxy, or rubber) is placed between the antenna and the body 20. The instrument 18 is also equipped with a signal generator mounted within the body (not shown) to pass an alternating current through the antenna. The signal generator operating frequency is generally between 1 kHz and 5 MHz. Alternatively, the current may be fed to the antenna through a wireline cable as known in the art.

As shown in Figure 5, when the instrument 18 is eccentered in the borehole, the metallic body 20 is exposed to the borehole fluid such that a local induced current distribution

is formed along the body 20. A shield 22 is also mounted on the body 20 to protect the TMD antenna and to permit the passage of particular desired electromagnetic energy components. U.S. Pat. Nos. 4,949,045 and 4,536,714 (both assigned to the present assignee) describe conductive metallic shield configurations that may be used. Those skilled in the art will appreciate that other suitable shields may be used with the instrument 18. For example, a shield may be configured in the form of a strip (not shown), also referred to as flex circuit, to provide flexibility and easy mounting.

For effective operation of the TMD antenna, the resulting current flow should not induce a voltage in the antenna. Thus if a conductive shield 22 is placed over the antenna so that current flows there instead of in the borehole fluid, a zero current will be induced in the antenna if the current in the shield 22 is azimuthally symmetric. Otherwise the voltage in the receiver antenna may be greater than it would be if current were flowing in the mud. The desired axisymmetric current distribution may be achieved by disposing a conductive material between the shield 22 and the body 20 such that an azimuthally uniform connection is formed. For example, a conductive metallic O-ring or gasket may be disposed at both ends of the shield 22 such that there are no breaks between the shield 22 and the body 20 (not shown). With respect to the embodiment of Figure 4, the conductive segment 16 on the non-conductive support redirects the induced current through the conductor centered through the TMD such that there will be zero voltage induced in the TMD within the mechanical accuracy of the placement of the conductor.

A zero current induced in the TMD antenna is also achieved by insulating the conductive shield 22 from the metallic body 20. This may be attained by mounting the shield 22 on the body 20 such that one end is fully insulated (not shown). Randallite, fiberglass-epoxy, rubber, or any suitable nonconductive material or compound may be disposed between the shield 22 and the body 20 to provide the desired insulation. Alternatively, the TMD may be sealed or potted onto the body 20 with a rubber over-molding or any suitable non-conductive compound that permits the passage of EM energy. Yet another embodiment comprises a shield 22 made of an insulating material to permit the passage of EM radiation. Useable materials include the class of polyetherketones described in U.S. Pat. Nos. 4,320,224 and 6,084,052 (assigned to the present assignee), or other suitable resins. *Victrex USA, Inc.* of West Chester, PA manufactures one type called PEEK. *Cytec Fiberite*, *Greene Tweed*, and *BASF* market other suitable thermoplastic resin materials. Another usable insulating material

is Tetragonal Phase Zirconia ceramic ("TZP"), manufactured by *Coors Ceramics* of Golden, Colorado.

Figure 6 shows another embodiment of the invention. A logging instrument with a non-conductive body is shown disposed within a borehole. The instrument is equipped with a transverse transmitter antenna Tx and a transverse receiver antenna Rx. The receiver antenna Rx is positioned between a pair of measure electrodes M, M′, which are themselves positioned between a pair of current electrodes A, A′. The electrodes M, M′, A, A′ may be formed as an array of circumferentially spaced apart metallic electrodes or as an annular electrode as described above.

One embodiment of the invention involves a process using the principle of superposition and a digital focusing approach. This embodiment is shown in flow chart form in Figure 7. This technique may be implemented with the embodiment of Figure 6. In this process, the transmitter antenna Tx is activated, at 100, and the voltage signal (V_{R1}) at the receiver antenna Rx as well as the voltage difference (ΔV_{M1}) on the measure electrodes M, M′ are obtained at 105, 110. The transmitter antenna is then shut off, at 115, and a current is run between the current electrodes A, A′ at 120. The voltage at the measure electrodes (ΔV_{M2}) and the voltage signal (V_{R2}) at the receiver antenna are again measured at 125, 130.

The excitation necessary to produce the set of voltages (ΔV_{M1}) on the measure electrodes M, M′ is then calculated, at 135, and the voltage in the receiver antenna Rx due to this excitation is computed at 140. This voltage is then subtracted from the voltage actually measured to produce the borehole-corrected signal at 145. Mathematically the equation is expressed as

$$V_{Corr} = V_{R1} - \frac{\Delta V_{M1}}{\Delta V_{M2}} V_{R2} . \qquad (1)$$

This voltage should be equal to the voltage that would appear on the receiver antenna Rx if the longitudinal current in the borehole did not exist in a high contrast situation. Since the transmitter antenna Tx operates at some finite frequency, and all the voltages are complex (they include an amplitude and a phase shift relative to the transmitter current or the electrode currents), the currents injected from the electrodes A, A′ are at the same frequency.

The instruments of the invention may be equipped with conventional electronics and circuitry to activate the sources and sensors to obtain the desired measurements as known in

the art. Once acquired, the data may be stored and/or processed downhole or communicated to the surface in real time via conventional telemetry systems known in the art.

Figure 8 illustrates the induced axial current flow encountered in the borehole with a typical non-conductive instrument equipped with a TMD when the TMD is perpendicularly eccentered in a conductive borehole. Figure 9 shows another embodiment of the invention. This particular embodiment entails a feedback process. The embodiment of Figure 9 is similar to that of Figure 6. The measure electrodes M, M′ are adapted to sample and measure the azimuthally varying magnitude of the induced electric field. Current is then injected into the borehole by the current electrodes A, A′ to counter or cancel the borehole current measured by the measure electrodes M, M′. Thus, current is discharged from the current electrodes A, A′ in such a way as to achieve the condition that the voltage difference between M and M′ is made equal to zero. That is $\Delta V = V_M - V_M = 0$.

Figure 10 shows another embodiment of the invention. The embodiment shown in Figure 10 is similar to that of Figure 9, except that the electrodes are disposed about a TMD receiver on a typical non-conductive instrument. With this configuration, the induced current flows up the borehole, enters the current electrode A′, travels up the instrument to the second electrode A, and continues up the borehole. In the immediate vicinity of the TMD, there is no current flow in the borehole. The measure electrodes M and M′ provide an analog feedback to the current electrodes A, A′ to just cancel the borehole effect. Thus, the flow of the axial current along the borehole is countered with the injection of another current emitted within the borehole.

The length of the electrodes E_1, E_2 necessary to intercept virtually all of the borehole current increases with the diameter of the borehole in which the instrument is run for embodiments of the invention using passive electrodes. This desire for a long electrode in order to reduce the borehole effect conflicts with the desire for short-spaced antenna arrays.

As shown in Figure 5, if the instrument body 20 is conductive, the borehole currents will close through the body and the current is localized near the TMD. The distance over which the currents fall off increases with the diameter of the borehole. If instead of having a full metal-body instrument, we have one with only a finite length conductive segment about the TMD, then for large boreholes only some of the current will return to the conductive segment. The rest will continue past the end of the conductive segment, resulting in incomplete cancellation of the borehole effect. This condition is shown in Figure 11a. As

discussed herein, one approach to remedy this situation is to actively drive a current between the electrodes E_1, E_2 so that all the borehole current closes on the electrodes.

Figure 11b shows another embodiment of the invention. A pair of monitor or measure electrodes M are added to the insulating portion of the instrument. If a current passes these electrodes, there will be an associated voltage ΔV. The condition for driving the electrodes E to eliminate this residual current is that $\Delta V = 0$. The feedback process for this embodiment is similar to that of Figure 9.

Other embodiments of the invention use a combined active-passive electrode E system. The electrodes E surrounding the transmitters or receivers can be used in both an active and passive role. In one such embodiment the transmitter is excited without driving the electrodes E (passive), then, after deactivating the transmitter, the electrodes E are separately driven (active) and a linear combination is formed as follows:

	Excitation 1	Excitation 2
Transmitter Current	I_1	0
Receiver Voltage	V_1	V_2
Electrode (M) Voltage	ΔV_1	ΔV_2

The combination is formed as:

$$V_{Corr} = V_1 - \frac{\Delta V_1}{\Delta V_2} V_2. \qquad (2)$$

The instrument measurement is then $\frac{V_{Corr}}{I_1}$. In this embodiment, the electrodes E are energized independently of the transmitter using conventional electronics. A passive-active embodiment may also be implemented by first shorting together the electrodes E while the transmitter is energized and then separately energizing the electrodes E after deactivating the transmitter. The passive use of the electrodes cancels out most of the borehole signal so that the active system has less to eliminate, improving system stability.

Another embodiment also uses two different excitations. The first excitation energizes the TMD while the electrodes E are shorted together. This produces a voltage at the receiver that is substantially free of borehole effect. The second excitation energizes the TMD while the electrodes E form an open circuit, so that no current flows between them. This results in a signal at the receiver with the full borehole effect. In this case $\Delta V_1 << \Delta V_2$.

	Excitation 1	Excitation 2
Transmitter Current	I_1	I_2
Receiver Voltage	V_1	V_2
Electrode (M) Voltage	ΔV_1	ΔV_2

As before,

$$V_{Corr} = V_1 - \frac{\Delta V_1}{\Delta V_2} I_2 ,$$

while in addition

$$I_{Corr} = I_1 - \frac{\Delta V_1}{\Delta V_2} I_2 . \qquad (3)$$

and the instrument measurement is then $\frac{V_{Corr}}{I_{Corr}}$.

This embodiment does not require an active circuit to energize the electrodes E; it includes a link between the electrodes that is operable between an open and short circuit state. This can be implemented with a conventional switch (e.g. a MOSFET switch) coupled into the conductor joining the electrodes E (not shown). An alternative embodiment for implementing this selective open-short state between the electrodes uses a ferrite or mu-metal core (e.g. a toroid) disposed on the conductor between the electrodes E (not shown). A conductive winding can be wrapped around the ferrite or mu-metal core (not shown) such that when the winding is opened the core acts as a "ferrite bead", introducing an impedance between the electrodes E to provide an open circuit. With a closed winding, the core acts as a low-impedance secondary for a transformer, greatly reducing the impedance on the conductor to provide a short. In essence, the core provides a selective choke to open or short the connection between the electrodes E. The core and windings can be implemented using conventional electronics as known in the art.

Figure 12 shows another embodiment of the invention. In this implementation, additional measure M and current electrodes E are disposed on insulating portions of the instrument. As shown in Figure 12, the placement of the electrodes E is not limited to any specific location on the instrument. The electrodes E may be placed near the transmitter, above the transmitter, surrounding the transmitter, or below the transmitter. The measure electrodes M can also be placed in various positions along the instrument, for example, in the middle of the receiver array or near the array as shown in Figure 12. An embodiment with the electrodes E placed below the transmitter and the measure electrodes above the receivers

allows for the entire array to be contained in a pressure compensated region with an insulating sleeve (not shown). It will be understood that the arrangement of transmitters and receivers is arbitrary. For example, the transmitter could be above the receivers or multiple transmitters could be placed between or around receivers as desired.

Active electrodes E can be made shorter compared to passive electrodes E to provide the desired signal cancellation. Another embodiment uses short passive electrodes E surrounding the transmitter combined with a set of active electrodes E near the transmitter (not shown). In this way the active circuitry is only needed to cancel any residual current along the borehole, providing for stabilized current cancellation in a short-spaced antenna array.

It will be appreciated by those skilled in the art that the borehole current falls off differently depending on alternative placements of the electrodes E relative to the transmitter. Thus measuring a voltage difference at a pair of measure electrodes and setting it different from zero at one point does not guarantee that the gradient will be equal to zero everywhere else along the receiver array. This is because the eccentered magnetic dipole of the transmitter can be thought of as inducing a vertical electric dipole moment. Attempting to counter the currents from this electric dipole with another electric dipole at a different position results in a source which still contains higher order moments and so cancellation cannot be insured everywhere. It will also be appreciated that the active systems of the various embodiments of the invention can be implemented either in hardware by the use of electronic feedback circuitry as known in the art, or through software calculation making use of the principle of superposition.

As known in the art, the signals measured with induction frequencies are affected by direct transmitter-to-receiver coupling. Therefore, the logging instruments of the invention may also include so-called "bucking" antennas to eliminate or reduce these coupling effects. It will also be understood by those skilled in the art that the principle of reciprocity provides that the electrode and/or conductive segment configurations of the invention will work whether they are implemented about the transmitters or receivers on the instrument. The spacing between the electrodes and/or antennas in the direction of the borehole may also be varied for effective implementation of the invention. In addition, the logging instruments of the invention may be "propagation" instruments in which quantities such as phase shift or attenuation could be measured between pairs of receivers.

While the methods and apparatus of this invention have been described as specific embodiments, it will be apparent to those skilled in the art that other embodiments of the invention can be readily devised which do not depart from the concept and scope of the invention as disclosed herein. All such similar variations apparent to those skilled in the art are deemed to be within the scope of the invention as defined by the appended claims.

CLAIMS

1. An apparatus for use in a borehole traversing a subsurface formation, the apparatus comprising:

an elongated support having a longitudinal axis;

at least one antenna disposed on the support such that its axis is tilted or perpendicular with respect to the support axis, each said antenna adapted to transmit or receive electromagnetic energy; and

a pair of electrodes disposed on the support, said electrodes linked to one another for joint electromagnetic interaction;

wherein the electrodes of said electrode pair are adapted to selectively form a short or open circuit between said electrodes.

2. The apparatus of claim 1, wherein the electrodes of said electrode pair are coupled together with a conductor.

3. The apparatus of claim 2, wherein said conductor comprises switching means to form an open or short circuit between said electrodes.

4. The apparatus of claim 1, wherein said at least one antenna is located between said electrodes.

5. The apparatus of claim 2, wherein said conductor comprises a conductive core disposed thereon and adapted to selectively increase the impedance in the coupling between said electrodes.

6. The apparatus of claim 1, wherein an electrode of the electrode pair is adapted to emit a current between said electrodes.

7. The apparatus of claim 1, further comprising a second pair of electrodes disposed on the support, said electrodes adapted to detect a current within said borehole.

8. The apparatus of claim 1, further comprising a second pair of electrodes disposed on the support, said electrodes adapted to emit a current between said electrodes.

9. A method for making a subsurface measurement, the method comprising:

a) transmitting electromagnetic energy from an antenna disposed within a subsurface borehole with its axis tilted or perpendicular with respect to the borehole axis;

b) detecting a current flow along said borehole, said current flow associated with the energy transmission of step (a), with a first pair of electrodes disposed within said borehole; and

c) emitting a current between a second pair of electrodes disposed within said borehole in response to the current flow detected at said first electrode pair to reduce said current flow; and

d) determining a voltage signal associated with the transmitted energy of step (a).

10. The method of claim 9, wherein step (b) comprises determining a potential between said first electrode pair.

11. The method of claim 9, wherein said antenna is positioned between the electrodes of said first electrode pair along said borehole.

12. The method of claim 9, further comprising disposing a third pair of electrodes within said borehole, said electrodes being shorted together by a conductor.

13. The method of claim 12, wherein said antenna is positioned between the electrodes of said third electrode pair and said conductor passes through said antenna.

Application No: GB 0317047.9 **Examiner:** S M Colcombe
Claims searched: 1-13 **Date of search:** 19 January 2004

Patents Act 1977 : Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1-13	US 2002/0105332 A1 (SCHLUMBERGER)

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art
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G01V

The following online and other databases have been used in the preparation of this search report :

WPI, EPODOC, JAPIO, OPTICS